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An Investigation of Heat Transfer in Vertical Shaft Kiln Process of Cement Manufacture: Part I - Convection

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Abstract— Packed bed heat transfer associated with the black meal vertical shaft kiln (VSK) process of cement manufacture was studied using varying feed sizes of the raw material and air flow rates using an experimental prototype. A computer controlled data acquisition system (DAS) was used to collect the experimental data on temperature across the kiln. Data was compared with available convective heat transfer models and it was observed that Mc Adams model best represents the studied system. The convective heat transfer studies indicated the optimum reaction front propagation speed for the maintenance of required clinkerization temperature. The air flow rate is suggested as 3000 litre per minute for a nodule size of ~ 9 mm diameter in the packed bed. The second part of the communication will be on the combined effect of conduction and radiation heat transfer in the system.
Keywords— Vertical Shaft Kiln (VSK), Packed bed heat transfer, effective heat transfer coefficient, convection, conduction.

I. INTRODUCTION

Because of its special economic and site specific advantages [1] production of cement using vertical shaft kiln (VSK) has been widely accepted in many countries worldwide. Manufacture of cement through vertical shaft kiln is made through a process called the black meal process, wherein the fuel, usually low volatile coal or breeze coke is inter-ground with raw material viz. lime stone, clay and additives, if any to form a homogenous powder called the black meal. Green nodules of size 8-12 mm Φ are prepared in a rotating disc nodulizer with spray of ~ 10% water and then fed in to the vertical shaft kiln where it is burnt by supply of compressed air from the bottom [2]. For the present heat transfer study a 30 kg capacity prototype is designed, fabricated and used to collect the experimental data. In the VSK cement manufacturing process drying and preheating occurs between 30-500 ^{0}C, calcinations occurs between 500-1300 ^{0}C and sintering occurs between 1300-1450 ^{0}C [3].

Heat transfer involving both mass and momentum plays a significant role in the performance of the vertical shaft kiln. VSK is essentially a packed bed column wherein the heat transfer occurs in a counter current flow of hot air from the bottom and solid granules of nodules/ clinker slowly moving vertically downward. In addition to this, there is also simultaneous drying, combustion, calcinations and other clinkering processes inside the kiln. There are three basic modes of heat transfer viz. convection, conduction and radiation inside the packed bed of the VSK. The involvement of each of these modes of heat transfer varies at different bed levels and temperature in the range of ambient to 1450^{0}C. In this paper only convective heat transfer inside the VSK is discussed. The combined effect of conduction and radiation will be presented in our next communication. The basic parameter for understanding the heat transfer by convection is the effective heat transfer coefficient, h_e which is determined experimentally and compared with heat transfer models suggested by earlier researchers for analogous systems.

II. REVIEW OF LITERATURE ON PACKED BED HEAT TRANSFER-CONVECTION MODE

Packed beds are hollow geometrical sections filled by packing materials. The most commonly used packed bed column geometry for different industrial applications is hollow cylinder. In a packed bed cylindrical column the fluid passes across the bed of particles at a relatively low velocity and gets resistance to percolate through the inter-particle voids. The particles retain their spatial entity and the bed behaves as a fixed bed [4]. Most of the heat and mass transfer studies are restricted to non reacting systems and information on chemically reacting system are very limited [5]. For a cylindrical packed bed, the models are usually one dimensional or two dimensional depending on the direction of heat flux/ temperature gradient along the axial or transverse direction

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of fluid flow [6]. In both these approaches the heat and mass transfer for the gas-solid system is considered as a single phase. The property values are assigned for a single continuous phase and the properties are termed *effective properties* which are dependent on the nature of the individual phases constituting the continuum [7]. The convective heat transfer is initiated from the conductive heat flux across the surface layer of the solid and is equal to the convective heat flux removed by the fluid in the thermal boundary layer. The mathematical representation of this phenomena is presented in equation (1-2)[8].

$$q_{surface} = -k_f\left(\frac{\partial T}{\partial y}\right)_{y=0} = h(T_S - T_\alpha) \quad \Rightarrow h = \frac{-k_f\left(\frac{\partial T}{\partial y}\right)_{y=0}}{(T_S - T_\alpha)} \qquad \text{----------------------------- (1)}$$

And for convective heat transfer over an area, the total heat transfer rate is

$$q = \int_A q_{surface}\, dA = (T_S - T_\alpha)\int_A h\, dA = hA(T_S - T_\alpha) \qquad \text{----------------------------- (2)}$$

Many researchers have studied packed bed heat transfer using different fluids, packing materials and heating methods. In most of the derived models Nusselt Number (*Nu*) is correlated with the Reynolds Number (*Re*) and Prandtl Number (*Pr*) [6, 9, 10]. The range of *Re* in the present scope of work is between 66.64 < *Re* < 145.38. Some of the widely used correlations within the scope of the present study are listed in Table I:

TABLE I
CONVECTIVE HEAT TRANSFER CORRELATIONS USED IN THE PRESENT STUDY

Equation No	Convective Heat Transfer Equations	Significance	Reference
3	$j_H = \frac{1.1}{(\mathrm{Re}_p^{0.41} - 0.15)} \quad \Rightarrow Nu = \frac{1.1\times \mathrm{Re}_p \times \mathrm{Pr}^{0.333}}{(\mathrm{Re}_p^{0.41} - 0.483)}$	6.71 < Re_p < 1000 Air as fluid	De Acetis and Thodos [11]
4	$\varepsilon\, j_H = 0.0108 + \frac{0.929}{(\mathrm{Re}_p^{0.58} - 0.483)} \quad \Rightarrow Nu = \frac{\mathrm{Re}_p \times \mathrm{Pr}^{0.333}}{\varepsilon}\left[0.0108 + \frac{0.929}{(\mathrm{Re}_p^{0.58} - 0.483)}\right]$	Re_p >20 Electrical heating	Gupta and Thodos [12]
5	$Nu = \left(1 + \frac{4(1-\varepsilon)}{\varepsilon}\right) + 0.5(1-\varepsilon)^{0.5}\,\mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.333}$	$3\times10^{-3} \le \mathrm{Re} \le 5\times10^{6}$ $0.2 \le \varepsilon \le 0.9$	Kuwahara et. Al. [13]
6	$Nu = 2.0 + 1.1\times \mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.333}$	Wide range of Re Forced convection	Wakao and Kaguei [10]
7	$Nu = 1.75\times \mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.333}$	$13 \le \mathrm{Re} \le 180$	Littman and Sliva [14]
8	$Nu = 1.10\,\mathrm{Re}\,\mathrm{Pr}^{0.333}/(\mathrm{Re}^{0.41} - 1.5)$	Re > 13	Bird et.al. [15]
9	$Nu = 2.0 + 1.8\times \mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.333}$	Re>50	Ranz and Marshall [16]
10	$Nu = (0.5\,\mathrm{Re}_{mod}^{0.5} + 0.2\,\mathrm{Re}_{mod}^{0.666})\,\mathrm{Pr}^{0.333}$	$10 < \mathrm{Re} < 10^4$ $\mathrm{Re}_{mod} = \rho_g u_g d_p / \mu_g (1-\varepsilon)$	Whitaker [17]
11	$Nu = 0.37\,\mathrm{Re}^{0.6}$	17 < Re < 70000	Mc Adams [18]

The correlations related to wall-to-bed heat transfer coefficient [6, 19] were not included in Table I as there is no significant radial temperature gradient at any particular axial distance of the bed in our present study.

III.EXPERIMENTAL SET UP

A prototype experimental kiln of cylindrical shape made of 3 mm mild steel plate, insulated by high alumina brick was fabricated. The height, internal diameter and insulation thickness of the kiln are 700 mm, 260 mm and 75 mm respectively. The experimental setup is shown in Fig. 1

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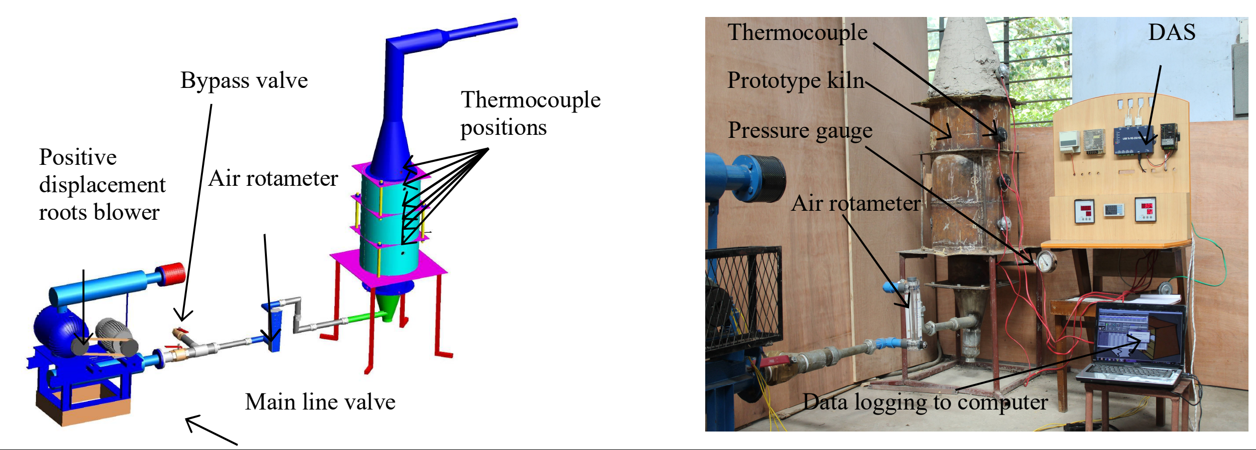

Fig.1 The experimental set-up

Air is introduced from a positive displacement roots blower through the conical section at the bottom of the kiln. A grate mechanism above the aforesaid conical section facilitates the air passage and prevents the solid granules from downward movement. The quantity of air supplied is measured by a rotameter and the temperature during the experiment is monitored across the kiln length at six different levels. The thermocouples are placed at a spacing of 60-120 mm. Type-B Platinum-30% Rhodium vs. Platinum-6% Rhodium thermocouples with DAS calibration in the range of 240-1700 ^{0}C are used in the experiment. The air flow rate to the kiln at three different levels is regulated through a bypass valve mechanism in the system. A data acquisition system (Make: Chino Corporation) is used for data logging.

IV. METHODS AND MATERIALS

A. Preparation of raw mix design and green nodule using pan nodulizer:

The black meal as referred earlier [2] was ground to 90% passing through 90 µm is homogenized and nodulized by water spray in a pan type nodulizer (Fig. 2). The green nodules of three different sizes as shown in table IV are prepared and used for the experiments. The chemical and proximate analysis of limestone, coke breeze and clay are determined by standard analytical procedures [20, 21] and presented in table II. Based on the results of the analysis raw mix design was made as per proportion and is shown in Table III.

TABLE II
RESULTS OF THE CHEMICAL ANALYSIS OF RAW MATERIALS USED

Limestone		Coke Breeze		Clay	
Parameters	Values	Parameters	Values	Parameters	Values
Loss on Ignition (LOI)	42.84 %	Moisture	5.64 %	Loss on Ignition (LOI)	12.44 %
Silicon Oxide (SiO_2)	0.91 %	Ash	34.68 %	Silicon Oxide (SiO_2)	54.10 %
Aluminium Oxide (Al_2O_3)	0.22 %	Volatile Matter	17.31 %	Aluminium Oxide (Al_2O_3)	16.34 %
Ferric Oxide (Fe_2O_3)	1.04 %	Fixed Carbon	42.37 %	Ferric Oxide (Fe_2O_3)	8.80 %
Calcium Oxide (CaO)	52.33 %	CV	6545 kcal/kg	Calcium Oxide (CaO)	2.62 %
Magnesium Oxide (MgO)	1.64 %	------	------	Magnesium Oxide (MgO)	1.13 %

TABLE III

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RAW MIX DESIGN FOR A 30 KG BATCH OF THE PROTOTYPE KILN

Raw materials	Values	Parameters	Values	Components	Values (%)
Limestone	21.18 kg	Lime Saturation Factor (LSF)	0.87	C_3S	37.11
Clay	5.71 kg	Alumina Ratio (AR)	1.57	C_2S	34.84
Coke breeze	3.11 kg	Silica Modulus (SM)	1.82	C_3A	11.59
Total Batch size	30 kg	------	------	C_4AF	14.22

B. Burning of the green nodules and temperature data acquisition

Nine sets of experiments were conducted using three different nodule sizes at three air flow rates of 2000, 2500 and 3000 litre per minute. For each of the experiments random packing was made and the bed parameters are presented in Table IV. The values of the packing parameters were found to be within the limit of spherical random packing arrangement [22].

TABLE IV
PACKED BED PARAMETERS FOR THREE DIFFERENT SIZED OF NODULES USED

Retained by sieve (mm)	Average diameter of nodules (mm)	Bed packing fraction (%)
+ 10	10.21	41.44
10-08	8.72	40.33
- 08	7.02	39.89

The properties of air viz. ρ_{air}, k_{air}, μ_{air}, $c_{p,air}$ were referred from literature [23] and were used for evaluation of Nusselt Number Nu, Reynolds Number Re and Prandtl Number Pr at different operating conditions of bed packing fraction and flow rates.

For each experiment the bed temperature (T_{bed}) and gas exit temperature (T_{go}) were experimentally determined for each flow rate and bed fraction. The entire height of the kiln was packed with the green nodules to determine the reaction front propagation speed V_{rfp} and the region of spacing between the thermocouples (40 mm) was used to determine the convective heat transfer coefficient (h_{exp}). The experimental convective heat transfer coefficient (h_{exp}) is calculated using the following correlation [8]

$$\frac{T_{bed}-T_{go}}{T_{bed}-T_{gi}} = \exp\left(-\frac{h_{exp}A_{p,t}}{\rho_{air}u_{air}A_{c,s}c_{p,air}}\right) \Rightarrow h_{exp} = \frac{\rho_{air}u_{air}A_{c,s}c_{p,air}}{A_{p,t}} \times \ln\left(\frac{T_{bed}-T_{gi}}{T_{bed}-T_{go}}\right) \qquad \text{---------------------------- (12)}$$

The reaction front propagation speed is calculated by dividing the distance between the two consecutive thermocouples by the time

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interval of the peak temperatures attained. A data acquisition system receives the thermocouple analog data and sends the data to a personal computer through an analog to digital converter (ADC). The acquired data are then stored in an inbuilt DAS software and the same is exported to Microsoft Office Excel 2007 for further analysis.

V. RESULTS AND DISCUSSIONS

Fig. 3 shows the plots of T_{bed} and T_{go} vs. time. It was observed that with the increase of the air flow rates the heating profile becomes steeper, indicating faster rate of reaction. About 36.71% of time to attain the desired clinkerization temperature was reduced when the flow rate was increased by 50%. However the retention time at the clinkerization temperature zone 1100 – 1450 – 1100^{0}C was more with lower air flow rate. It was also observed that even at higher air flow rate, the retention time was more for larger size of nodules. This is due to the reason that because of the presence of more fuel in larger nodules more time is required for the combustion process and also helps in retention of heat inside the burnt clinker. The significance of retention time in VSK process for cement manufacture is important to maintain clinker quality [2].

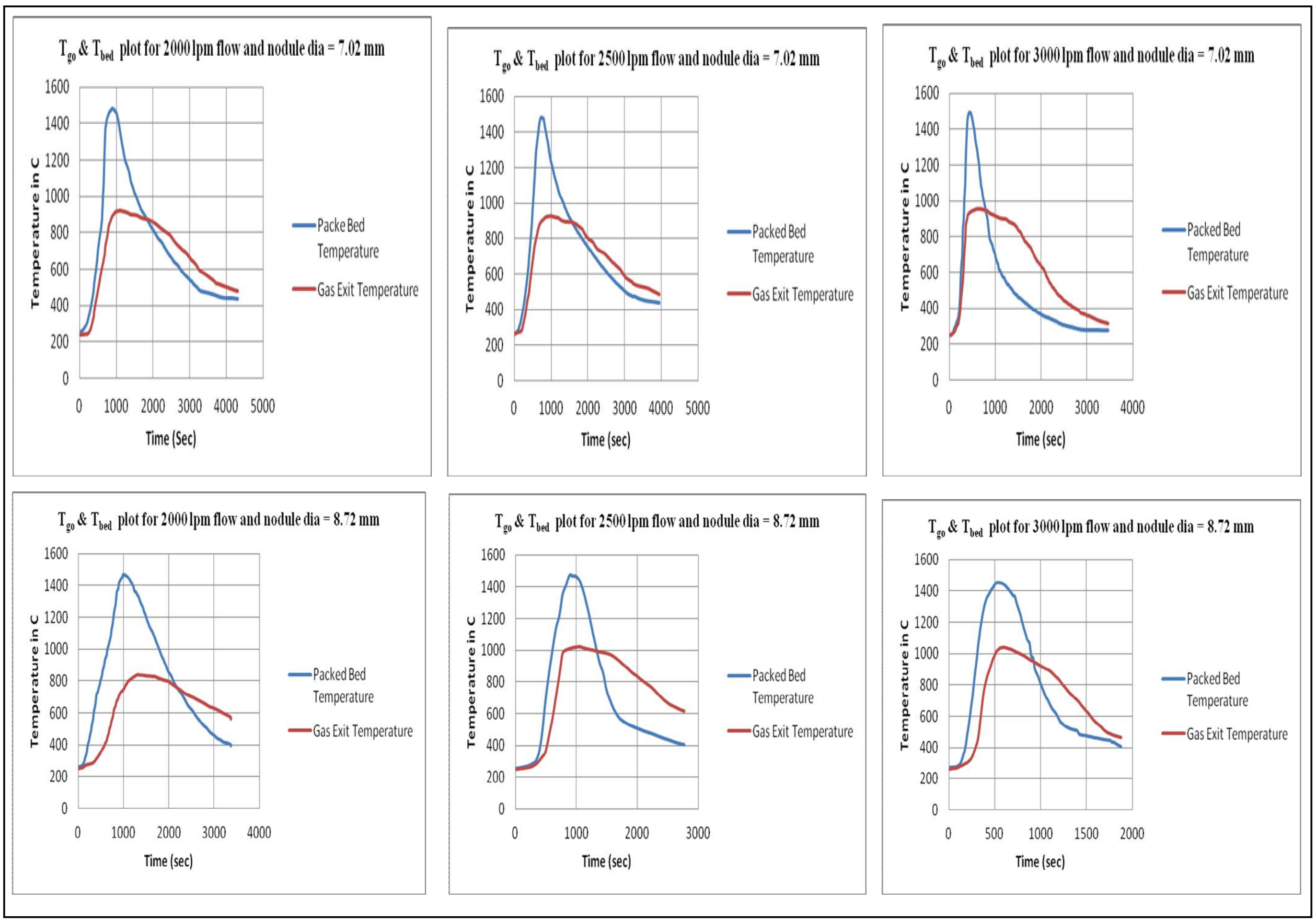

Fig. 3 Temperature profiles at various air flow rates and nodule sizes

The Nusselt Number *Nu* for identified correlations (Table I) were determined for all the variations in flow rate and nodule sizes and compared with the experimental value as shown in Fig.4. It is observed that the model equation proposed by Mc Adams [18] best represents the experimental values.

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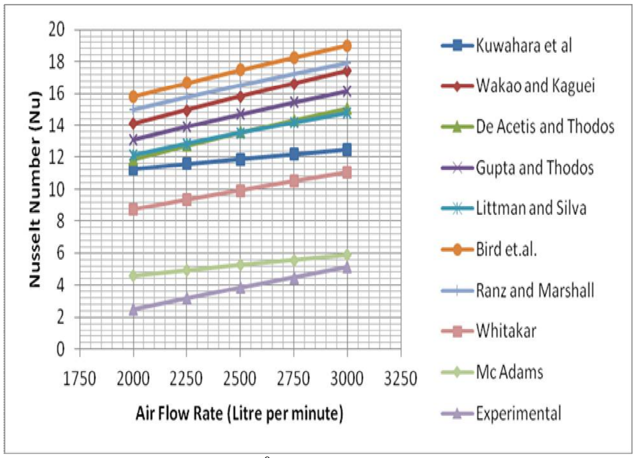
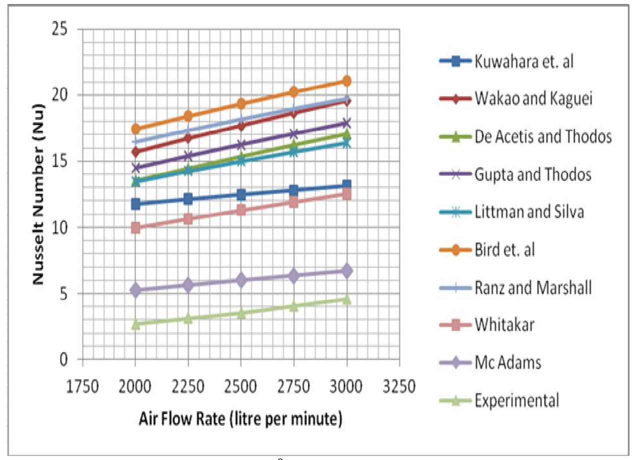
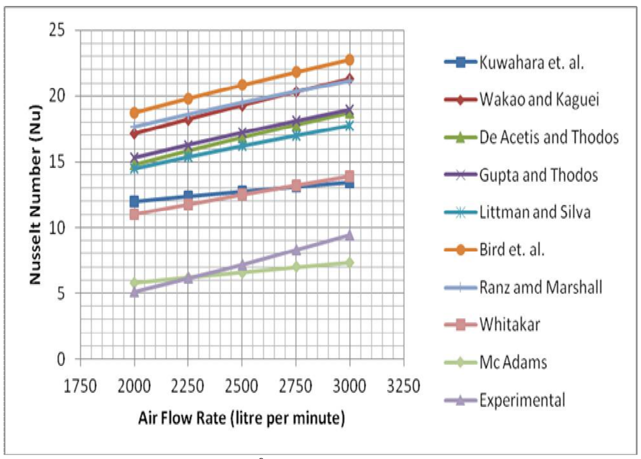


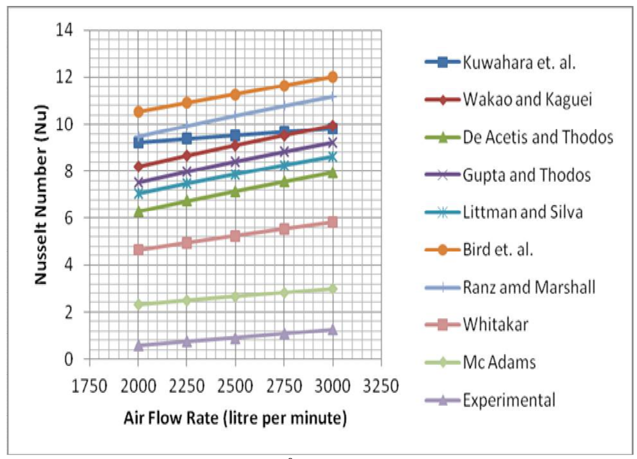
T_{bed} = 500 ^{0}C and d_p = 7.02 mm



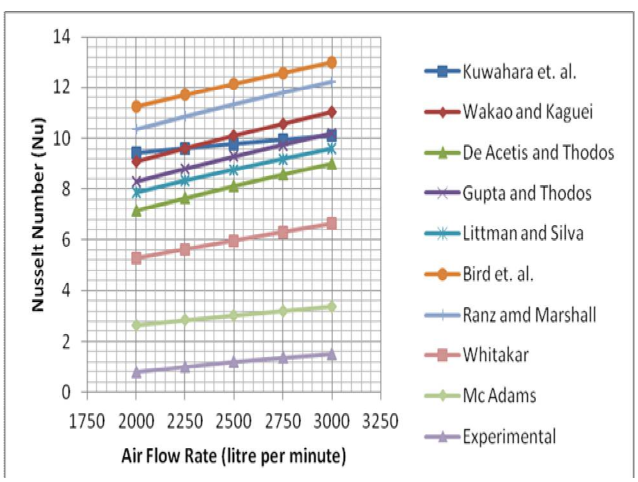
T_{bed} = 500 ^{0}C and d_p = 8.72 mm



T_{bed} = 500 ^{0}C and d_p = 10.21 mm



T_{bed} = 1300 ^{0}C and d_p = 7.02 mm



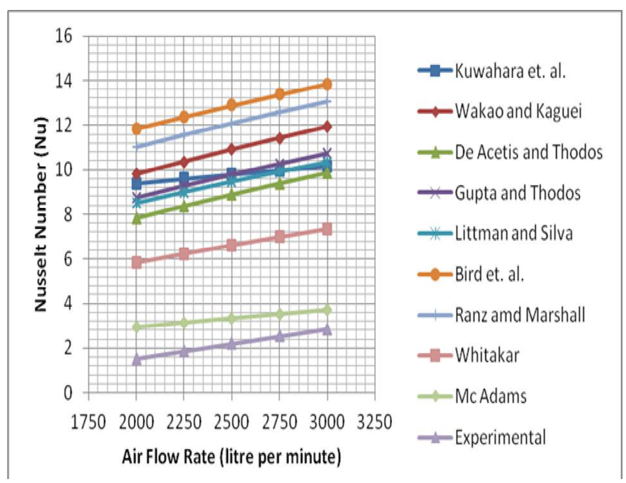


Fig. 4 Nusselt Number for theoretical and experimental results

The best fitting Mc Adams model was used to determine the effect of varying nodule sizes on the Nusselt Number. The observations are shown in Fig. 5. It is observed that the convective heat transfer coefficients increases with the increase of the nodule size. This is because of the reason that with the increase of nodule diameter the packing fraction increases and this allows more paths to the air to

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flow through the packed bed resulting more convective transfer of heat.

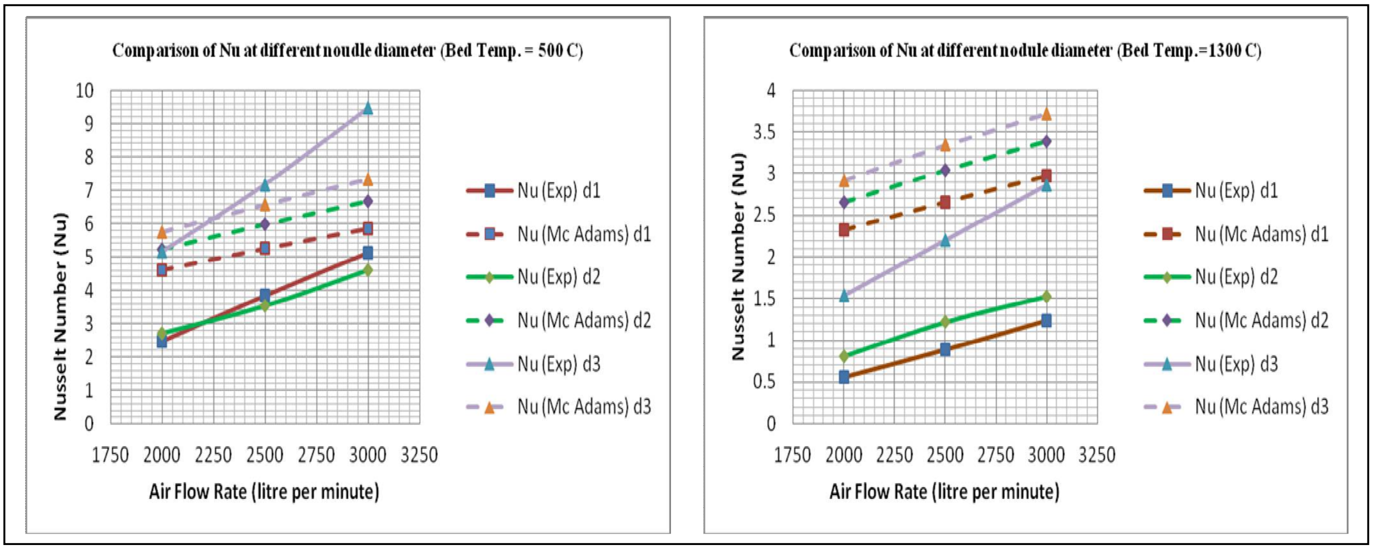
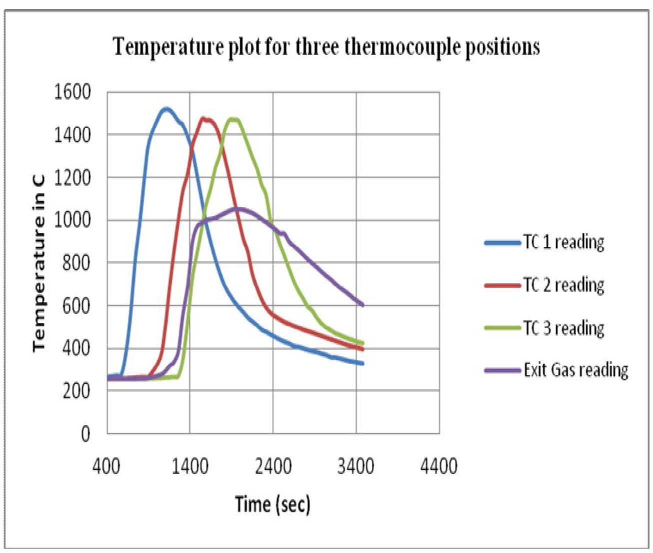
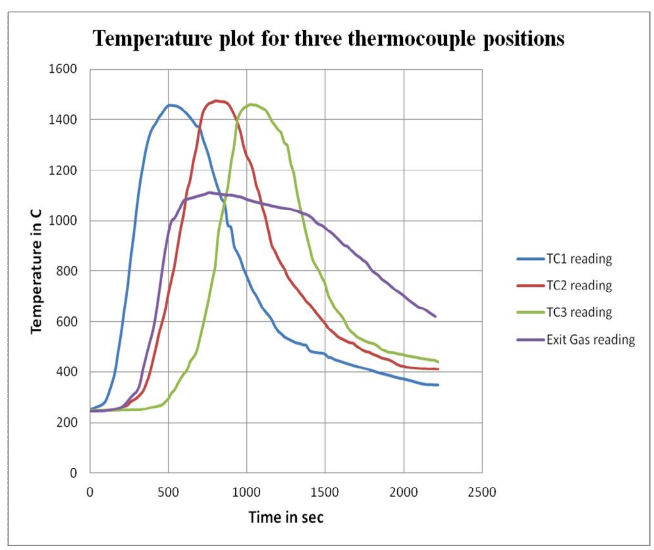


Fig.5 Comparison of Nusselt Number (Nu) for different nodule diameter.

The reaction front propagation speed V_{rfp} was determined as the ratio of axial distance between two consecutive temperature measuring points and the average time taken to achieve the maximum bed temperature $(T_{bed})_{max}$. Fig.6 shows the plot of T_{bed} and T_{go} vs. time which was used for evaluating the V_{rfp} (Table. V). It is observed that the reaction front propagation speed increases with the increase of air flow rate. This is due to the availability of more air for facilitating the faster combustion.



For Q = 2500 lpm and d_p =8.72 mm



For Q = 3000 lpm and d_p =8.72 mm

Fig.6 plots of T_{bed} and T_{go} vs. time for three thermocouple positions TC1, TC2 and TC3

TABLE V
REACTION FRONT PROPAGATION SPEED FOR DIFFERENT FLOW RATES

Average nodule diameter (mm)	Air flow rate (litre per min)	Average reaction front propagation speed (mm/min)
7.02	2000	3.45
	2500	4.75
	3000	8.83
8.72	2000	3.64
	2500	5.81
	3000	9.74
10.21	2000	5.66
	2500	5.82
	3000	7.69

VI. CONCLUSIONS

It can be concluded from the investigation that in the packed bed of vertical shaft kiln process of cement manufacture, one dimensional (axial) unsteady state heat transfer is best represented by the Mc. Adams heat transfer model within the limit of the clinkerization temperature and allowable variations of feed nodule size. Another observation was the reaction front propagation speed (V_{rfp}) which indicated that a speed of 9.74 mm per minute is an optimum for maintaining the retention time and achieve the required clinkerization temperature at an air flow of 3000 lpm. Further studies on combined effect of conduction and radiation will provide helpful information for scale-up design of the vertical shaft kiln for manufacture of cement.

VII. NOMENCLATURES

A : Area (m^2)
$A_{c,s}$: Cross sectional area of solid bed (m^2)
$A_{p,t}$: Total surface area of the particles (m^2)
c_p : Specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
C_3S : Tricalcium Silicate
C_2S : Dicalcium Silicate
C_3A : Tricalcium Aluminate
C_4AF : Tetracalcium Aluminoferrite
d : Diameter (m, mm)
h : Convective heat transfer coefficient ($Wm^{-2}K^{-1}$)
j_H : Colburn j factor = $Nu / (Re\ Pr^{1/3})$
k : Thermal conductivity ($Wm^{-1}K^{-1}$)
Nu : Nusselt Number = (hd_p / k_f)
Pr : Prandtl Number = $(\mu c_p / k_f)$
q : Rate of heat flow (W)
Re : Reynolds Number = $(\rho u d_p / \mu)$
T : Temperature (K)
u : Velocity of air ($m\ s^{-1}$)
V_{rfp} : Reaction front propagation speed ($mm.min^{-1}$)
x, y, z: Coordinates
ρ : Density ($kg\ m^{-3}$)
μ : Viscosity (Pa.s)

Subscripts

c : Cross sectional
f : Fluid
g : Gas
i : In
o : Out
mod : Modified
p : Particle, Pressure
rfp : Reaction front propagation
s : Surface, Solid
t : Total
α : Ambient

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